Models of the origin of EGMF

Kandaswamy Subramanian [a]

[a] Inter-University Centre for Astronomy and Astrophysics,
Pune 411 007, India.

Plan

- **The universe is magnetized:**
- **Need Coherent seed fields and Dynamos**
- **Origin in the early Univserse?**
- **Cosmic Batteries?**
- **The turbulent fluctuation dynamo: Young galaxies, clusters, IGM?**
- **The turbulent helical large scale (galactic) dynamo**
- **Main Problem: Coherence in presence of noise? Helicity?**

A. Brandenburg & K. Subramanian, Physics Reports, 417, 1-205 (2005)
K. Subramanian, A. Shukurov, N. Haugen, MNRAS, 2006, 366, 1437
K. Subramanian, "Magnetizing the Universe", PoS proceedings, arXiv:0802.2804
K. Subramanian, Magneic fields in the early universe, AN, 2010, 331, 110

The magnetic Universe

- **Earth** (1 Gauss; Irregular reversals over 2×10^5 yr)
- **Sun** (1 - 10^3 gauss; 11 yr Solar cycle)
- **Galaxies** (10 micro Gauss; ordered: 10 kpc)
- **Clusters of Galaxies** (microgauss, 10 kpc scales)
- **Young galaxies** (microgauss)
- **Inter galactic medium?** ($B \geq 3 \times 10^{-16}$ Gauss; Mpc scales)

How do these fields arise?

Maintaining magnetic fields

- **Magnetic fields decay if not maintained, because of:**
  - Resistance dissipating currents ($\sim 20,000$ yr for earth)
  - Lorentz force Driving motions, which are damped by Viscosity or become turbulent and then decay
- **EM induction by Motions can maintain magnetic fields**

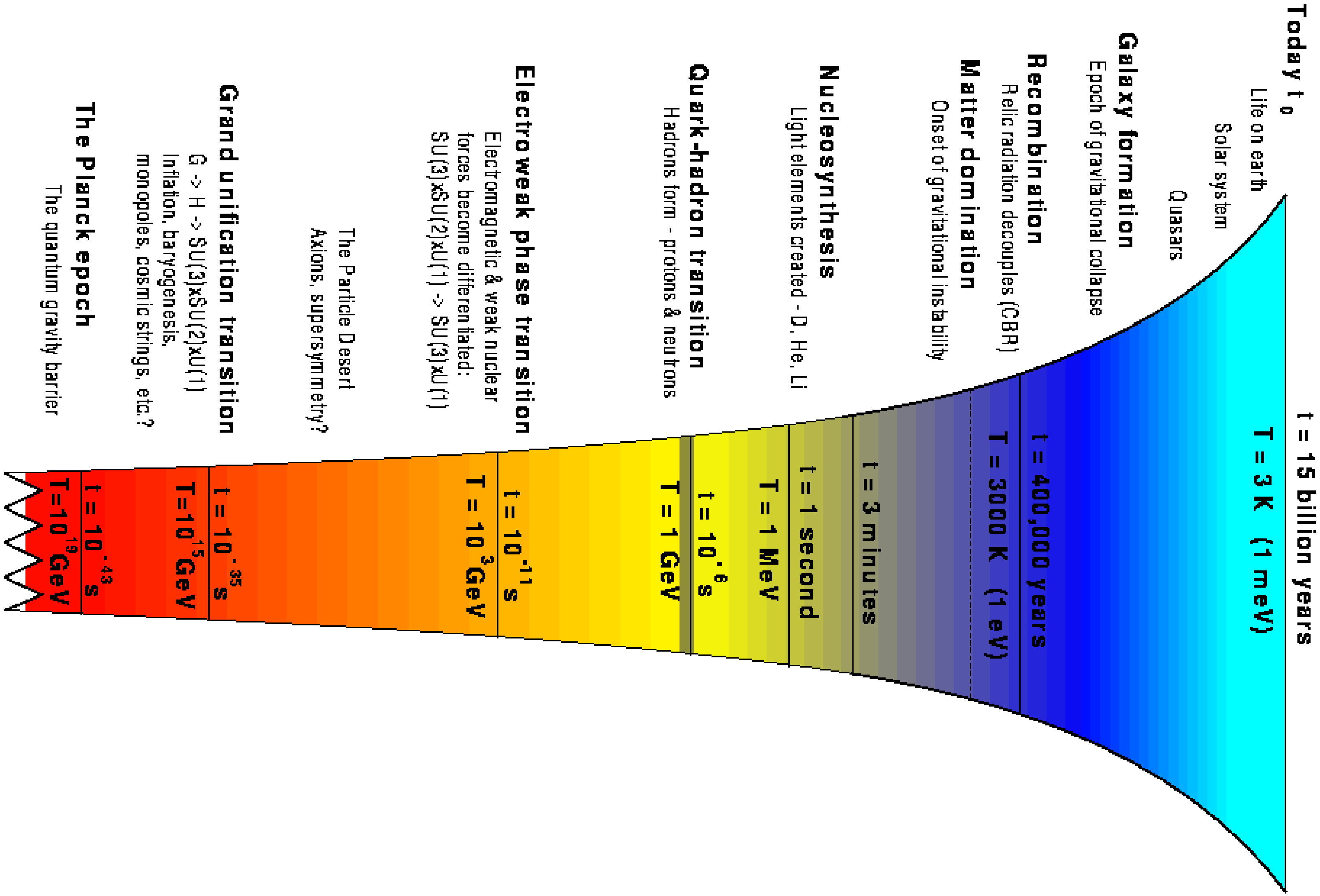
$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}, \quad \boldsymbol{E} = -\boldsymbol{U} \times \boldsymbol{B} + \frac{\boldsymbol{J}}{\sigma}.$$

- **Motion in a magnetic field induces electric fields**
- **If this electric field has a curl, can re-generate magnetic fields**

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\boldsymbol{U} \times \boldsymbol{B}) + \eta \nabla^2 \boldsymbol{B}.$$

- **Magnetic Field almost frozen to moving plasma.**
  Need initial seed field – Early Universe? Batteries?
  Need kinetic to magnetic energy conversion — dynamos

Early Universe timeline



(http://www.damtp.cam.ac.uk/research/gr/public/images)

Primordial fields from Inflation?

Origin during Inflation: (Turner and Widrow, PRD, 1988; Ratra 1992)

- Rapid expansion $\rightarrow$ vacuum fluctuations amplified and stretched to long wavelength "classical" fluctuations
- Negligible charge density breaks flux freezing.
- BUT Need to break conformal invariance of ED
- EM wave amplified from vacuum fluctuations
- After reheating $\mathbf{E}$ shorted out and $\mathbf{B}$ frozen in.

$$(d\rho_B/d\ln k) = \left(C(\gamma)/2\pi^2\right) H^4 (-k\eta)^{4+2\gamma} \approx (9/4\pi^2)H^4 \quad (\text{for } \gamma = -2)$$

$$B_0 \sim 5\times 10^{-10}\text{G}\left(\frac{H}{10^{-5}M_{pl}}\right) \qquad \text{(KS, 2010)}$$

- Exponentially sensitive to parameters, as need $B \sim 1/a^{\epsilon}$
- Need huge growth of charge: a Problem? (Demozzi et al, 2009)

IUCAA

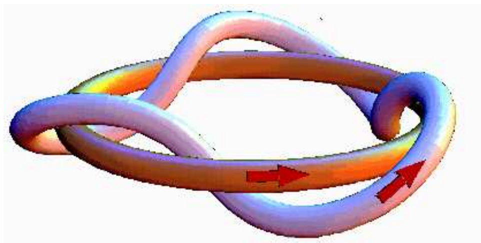
From Electroweak/QCD Phase transition?

- **Correlation scale usually tiny:** $H^{-1} \sim 1$ **cm (EW) or** $\sim 10^4$ **cm QCD phase transition or comoving** $R_H \sim 100\mathrm{AU}/0.1$ **pc**

- **Unless Helicity generation/Conservation leads to Inverse Cascade** (Brandenburg et al, PRD 96, Banerjee & Jedamzik, 2004)

- **Magnetic Helicity** $H = \int_V \mathbf{A} \cdot \mathbf{B}\, dV$, $\nabla \times \mathbf{A} = \mathbf{B}$
  $\mathbf{A}$ **is vector potential**, V **is closed volume**

- **Measures links and twists in** $\mathbf{B}$

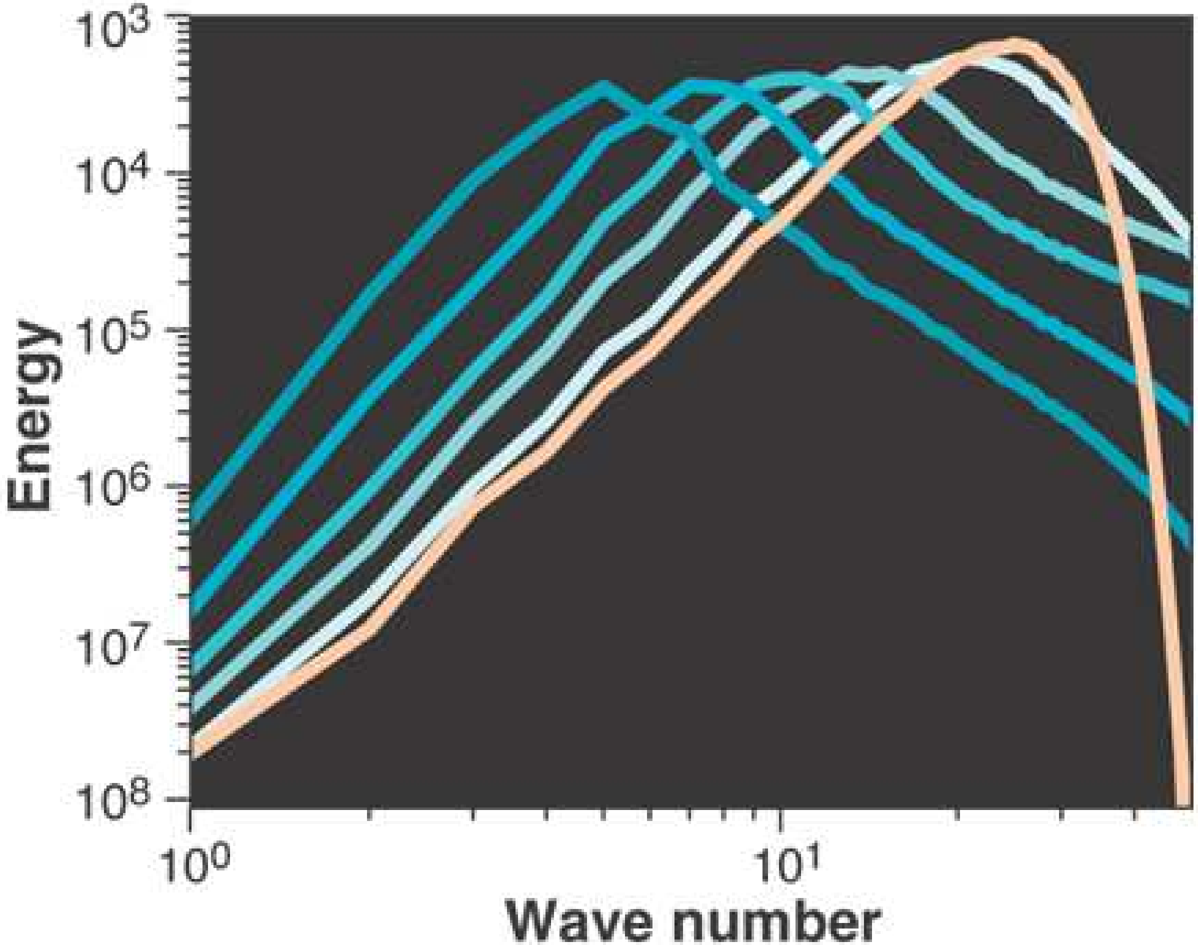


- **Helicity is nearly conserved even when energy dissipated**

- **Helicity generation during EW baryogenesis:** $H/V \sim n_b/\alpha$!
  (Vachaspati, 2001; Copi et al 2008; Diaz-Gil et al, 2008)

Inverse cascade of helical B

(Christensson, Hindmarsch, Brandenburg, 2001; Brandenburg 2001)



- **Assuming helicity conservation,** $H \sim LB^2 \sim LE \sim$ **constant.**
- **so** $dE/dt \sim E/(L/v) \sim E^{5/2}/H \rightarrow L \propto B^{-2} \propto t^{2/3}$ (Sim. $L \propto t^{1/2}$).

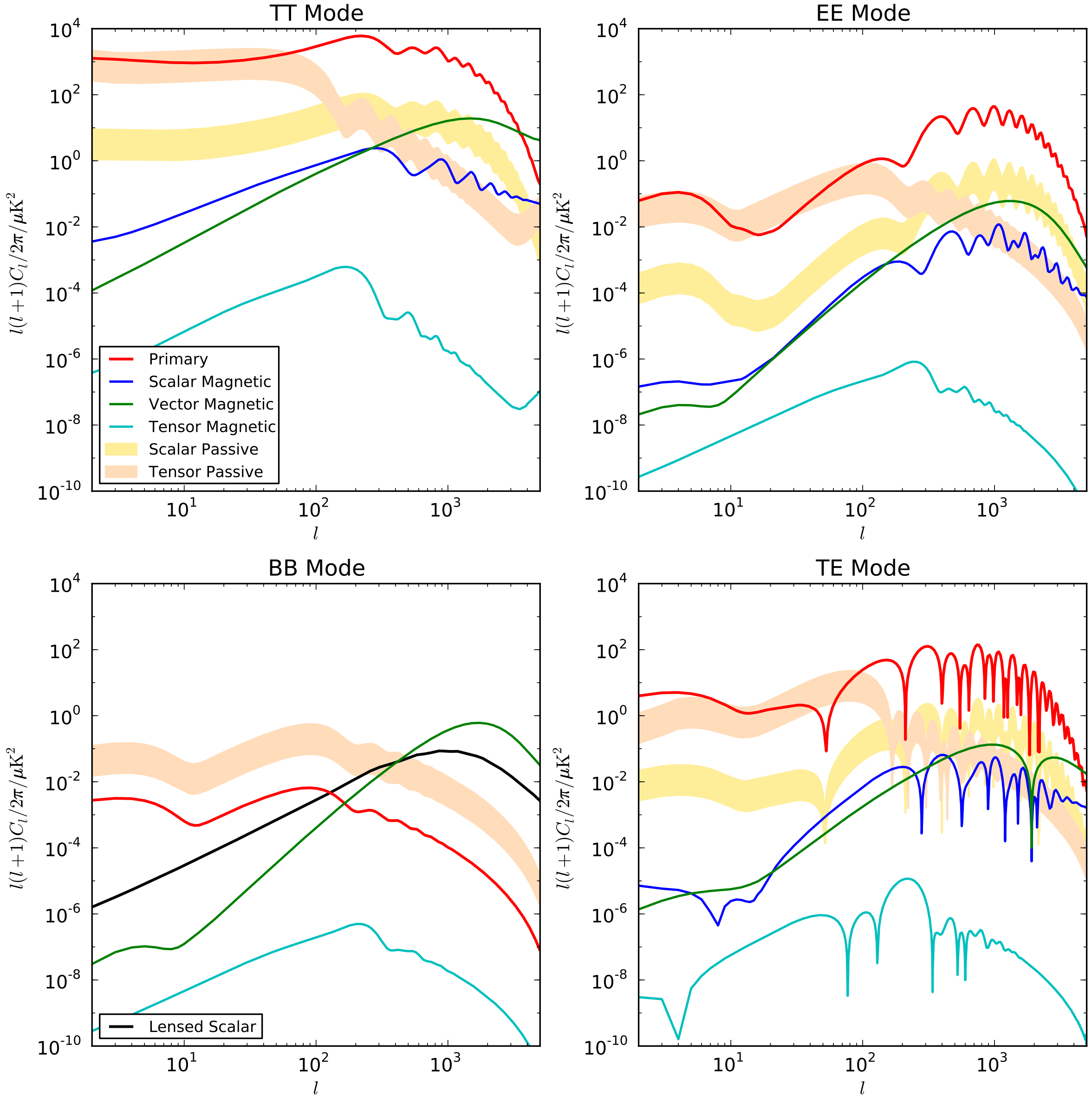
Probing Early Universe B

- $B^2/(8\pi\rho_{rad}) \sim 10^{-7} B^2_{-9}$. Here $B_{-9} = B_0/(10^{-9}G)$
- Magnetic stress $\Rightarrow$ metric perturbations, including Grav. Waves
- Lorentz force $\mathbf{J} \times \mathbf{B}/c \Rightarrow$ almost incompressible motions
- Overdamped by radiative viscosity, unlike compressible modes. Survives damping for $L_A > (V_A/c) L_{Silk} \ll L_{Silk}$ (Jedamzik et al, 1998; Subramanian, Barrow 1998)
- **CMB anisotropies from metric and velocity perturbations:** **Intrinsically Non Gaussian** (Seshadri, Subramanian, PRL, 2009; Caprini et al, JCAP, 2009; Trivedi, Subramanian, Seshadri, PRD, 2010)
- Post recombination: $n_{rad}/n_b \gg 1 \Rightarrow$ compressible motions $\Rightarrow$ seeds $\delta\rho/\rho \Rightarrow$ First Structures
- B field Dissipation $\rightarrow$ Ionization, Heating, Molecules

Coherent primordial nG fields potentially detectable

CMB signals: scalar+Tensor + Vector

$B_\lambda = 4.7\mu\text{G}, n \sim -3$, Including passive component, Shaw & Lewis, arXiv:0911.2714



Astrophysical "seed" field mechanisms

- **Astrophysical Batteries using postive/negative charge asymmetry**

- **Biermann Batteries**: $\mathbf{E}_{Bier} = -\nabla p_e/en_e + ...$

$$(\partial \mathbf{B}/\partial t) = -c\nabla \times \mathbf{E}_{Bier} = -(ck/en_e)\nabla n_e \times \nabla T_e$$

  - **If E_{Bier} has a curl then from Faraday, B can be generated**
  - **Re-Ionization fronts**: $B < 10^{-19}$ G (Subramanian et al 1994, Gnedin et al, 2000),
  - **Structure formation Shocks** (Kulsrud et al, 1997)

- **During recombination**: $B_0 \sim 10^{-30}$ G at MPc (Gopal & Sethi, 2005; Mattarrese et al, 2005); $B_0 \sim 10^{-21}$ G at pc (Ichiki et al 2007)

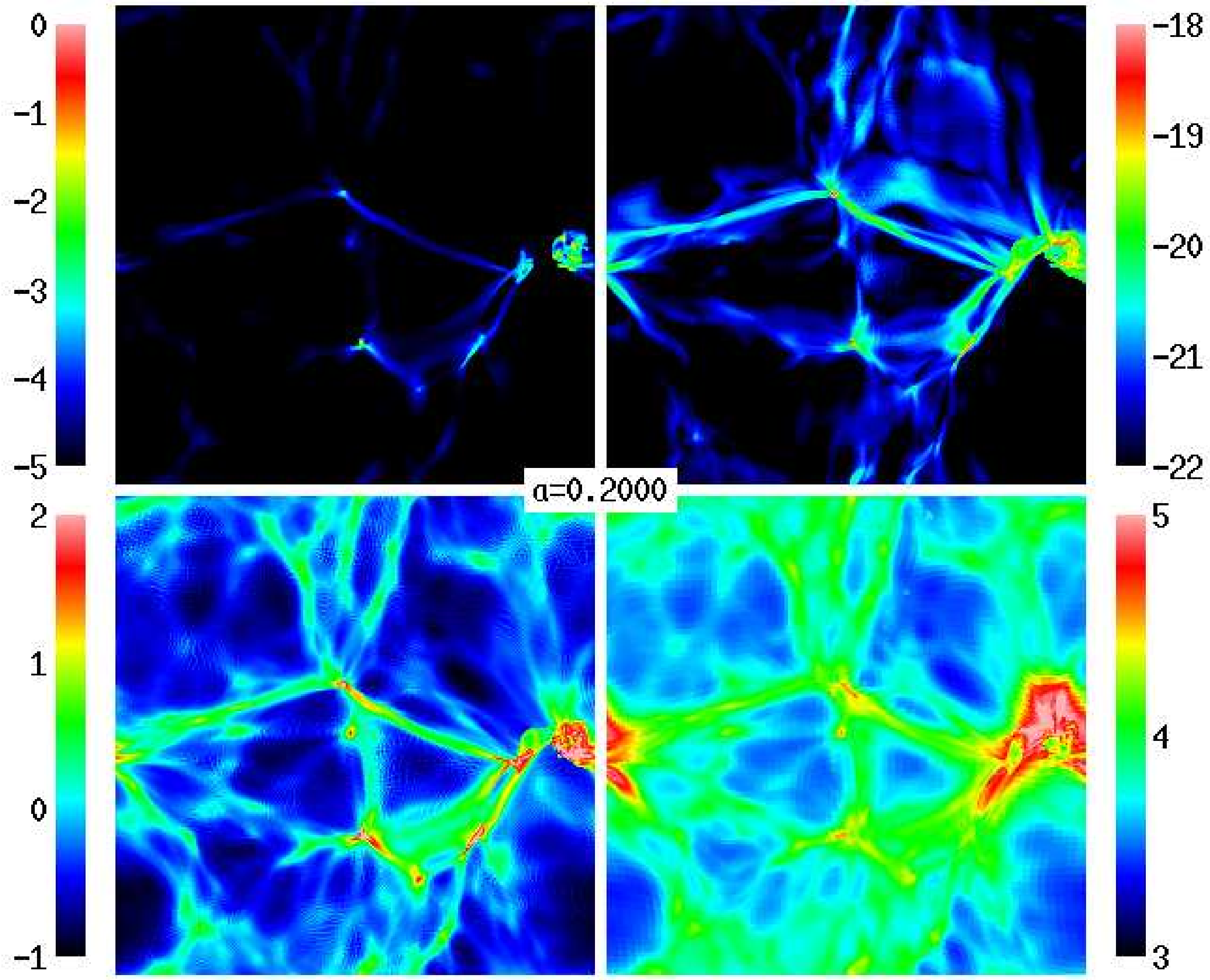
- **Cosmic Ray induced generation?** (Miniati, Bell 2010)

- **Seed fields from first supernovae and AGN outflows**

Need Dynamos to explain observed fields and maintain against decay

Magnetic fields from Reionization

HI, gas density, temperature and B field; Gnedin, Ferrara, Zweibel, 2000, ApJ

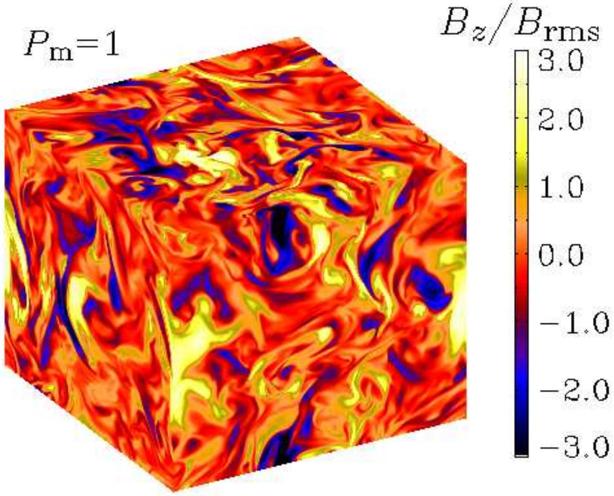


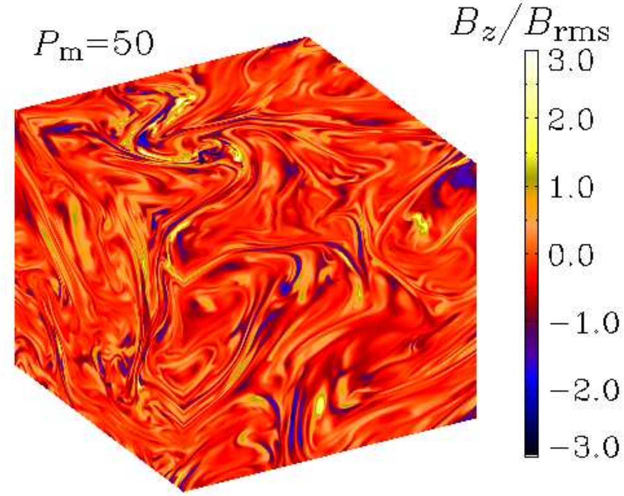
Small scale turbulent dynamo

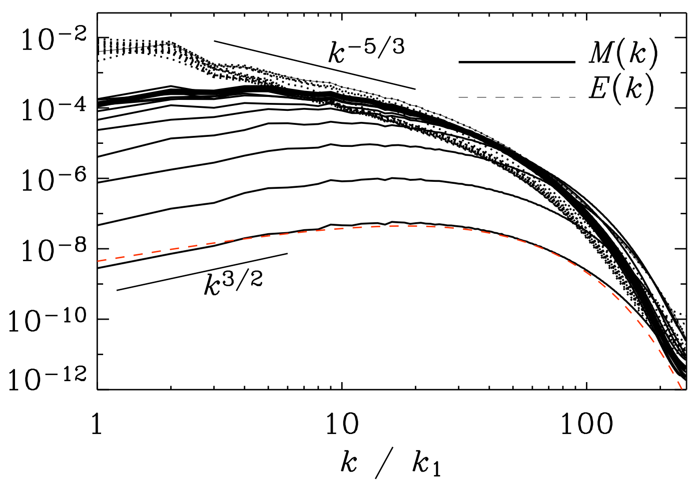
- **Turbulence common in the cosmos: Stars, galaxies, galaxy clusters, IGM?**
- **Turbulence leads to Random Stretching of magnetic flux;**
- **Then Flux freezing $\Rightarrow$ Growth of B**
- $BA =$ **constant and** $\rho AL =$ **constant** $\rightarrow B/\rho \propto L$, **and** $A \propto 1/(\rho L)$
- **Resistance limits growth when** $v/L \sim \eta/l_B^2$ **or** $l_B \sim L/R_{\mathrm{M}}^{1/2}$
- **Random B grows if** $R_{\mathrm{M}} = VL/\eta > R_{crit} \sim 30 - 100$ (Kazantsev 1967)
- **Growth rate fast** $\sim v/L$ (10^7 **yr: Galaxies;** 10^8 **yr clusters)**
- **Field intermittent, curved on scale L, squeezed to small transverse scales** $\sim L/R_m^{1/2} \ll L$

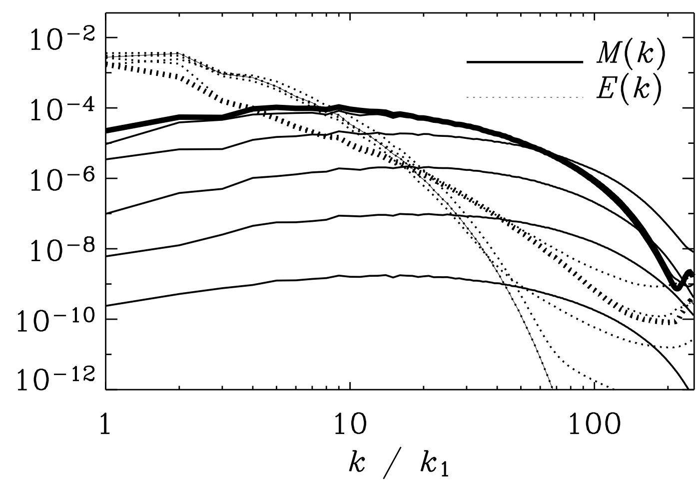
Fluctuation dynamo simulations

Generated B intermittent :Simulations by Axel Brandenburg, 2005





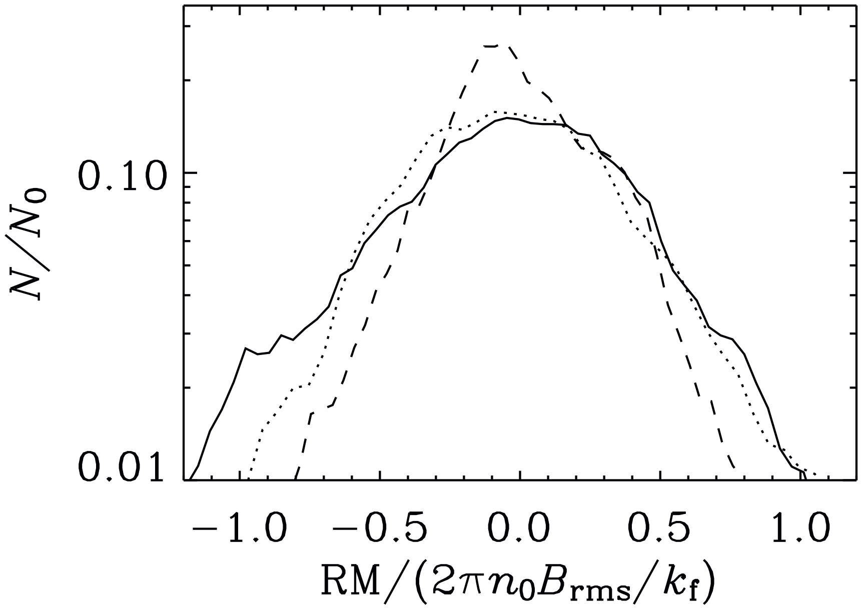




Fluctuation dynamo saturation?

- **Renormalized η drives efective $R_{\rm M} \rightarrow R_{crit}$, $l_B \sim L/R_{crit}^{1/2}$,**
  Saturated state universal (Subramanian, PRL, 1999; 2003).

- **Faraday RM Histogram for $P_m = 1, 1/4, 30$; explains cluster RM**
  (Subramanian, Shukurov, Haugen, MN, 2006) (Ensslin, Vogt, A&A 2006)

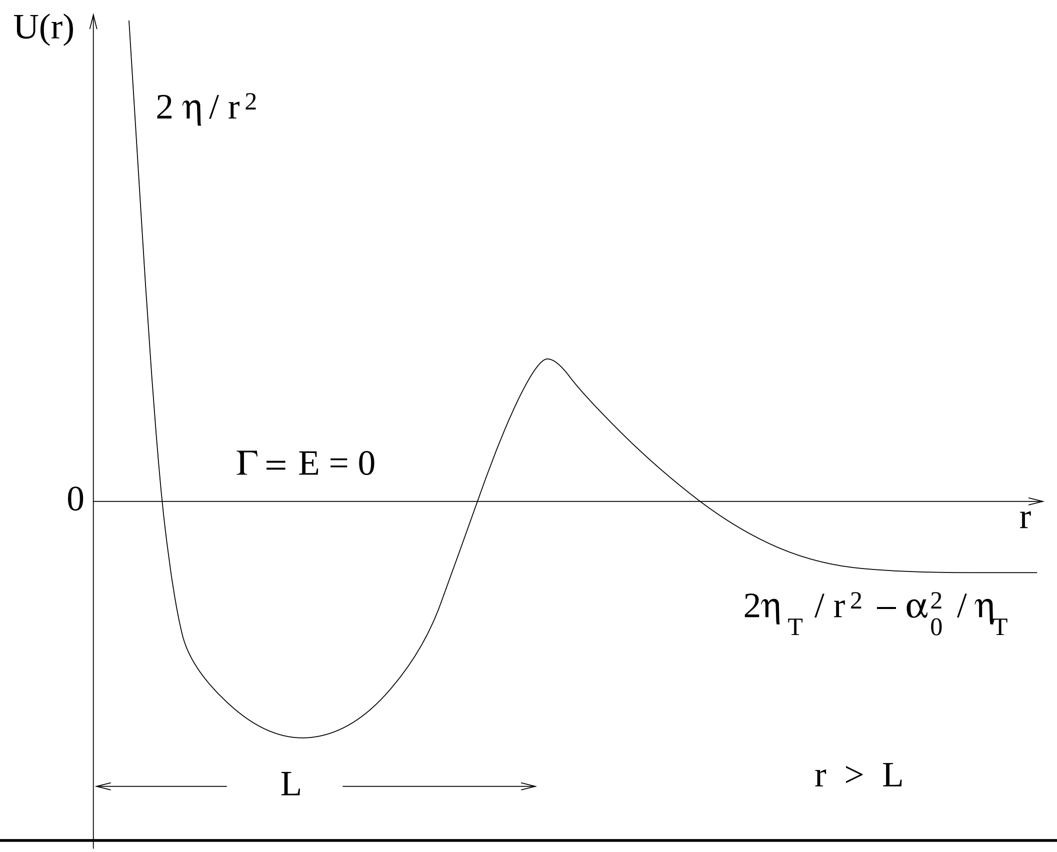


- **Saturation due to Reduced stretching BUT $l_B \sim L/R_{\rm M}^{1/2}$!**
  Plasma effects crucial (Schekochihin, Cowley et al., ApJ, 2004, 2006)

Important for Cluster/young galaxy/IGM Faraday RM

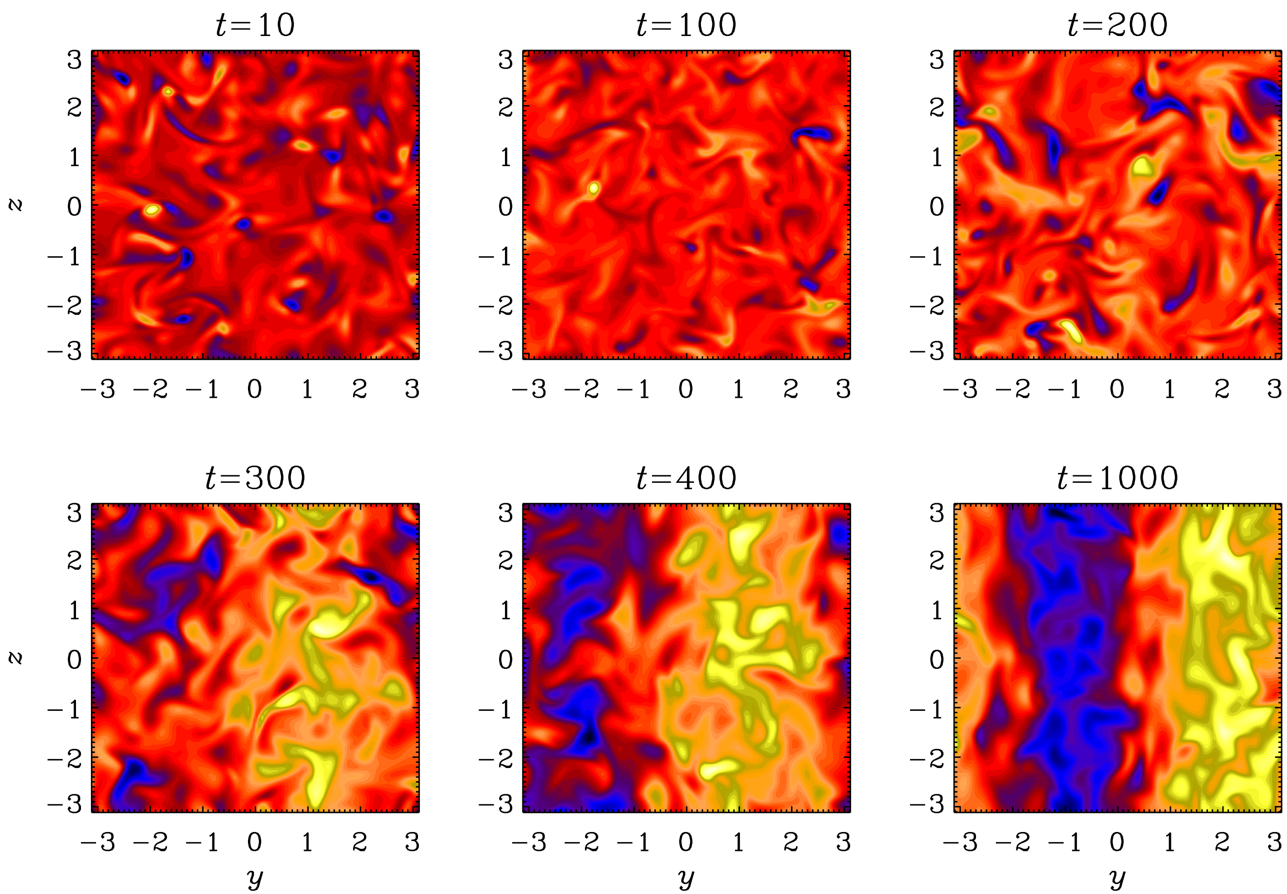
Kazantsev with Helicity: Tunneling?

- **Helicity of turbulence allows 'tunneling' to larger scales than L** (Subramanian, 1999, PRL; Brandenburg, Subramanian, A&A Lett, 2000)
- **For** $\dot{M}_{\rm L} \approx 0$, $\dot{H} \approx 0 \rightarrow -\eta_{\rm T}(d^2\Psi/dr^2) + \Psi\left[U_0 - (\alpha^2(r)/\eta_{\rm T}(r))\right] = 0$,
- $r \gg L$, $M_{\rm L}(r) = \bar{M}_{\rm L}(r) \propto r^{-3/2} J_{\pm 3/2}(\mu r)$,



Helically forced turbulent dynamos

Axel Brandenburg, Ap.J. 550, 824 (2001)



Rapid growth in kinematic stage conserving helicity.

Further Slow Growth on resistive timescale (dissipating small-scale helicity)

Turbulent Mean-Field Dynamo: Galactic

- $\mathbf{U} = \overline{\mathbf{U}} + \mathbf{u}$, $\mathbf{B} = \overline{\mathbf{B}} + \mathrm{b}$: **Mean + Stochastic fields**
- **Mean field satisfies DYNAMO equation**

$$\frac{\partial \overline{\mathbf{B}}}{\partial t} = \nabla \times \left(\overline{\mathbf{U}} \times \overline{\mathbf{B}} + \overline{\boldsymbol{\mathcal{E}}} - \eta (\nabla \times \overline{\mathbf{B}}) \right);$$

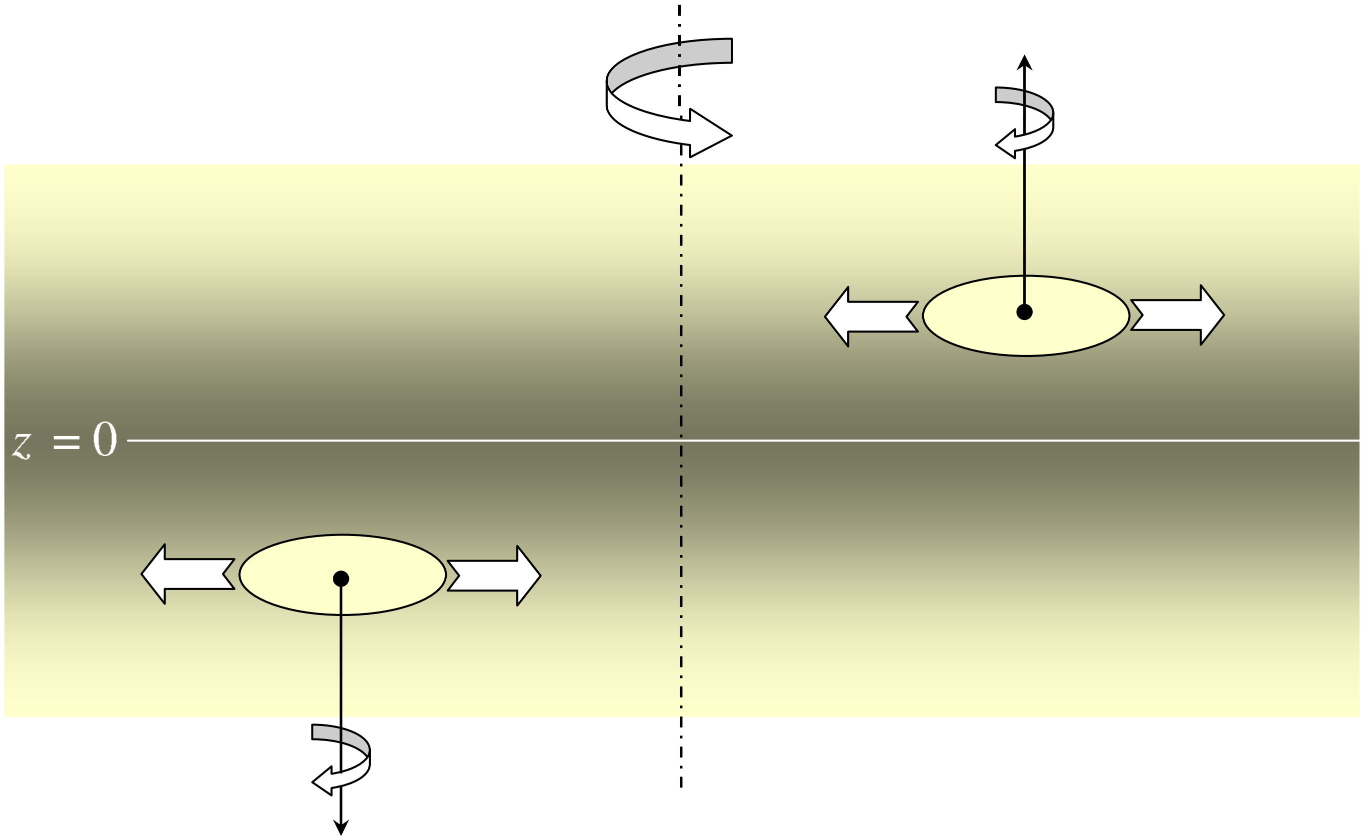
- **Finding** $\overline{\boldsymbol{\mathcal{E}}} = \overline{\mathbf{u} \times \mathrm{b}}$ **is a closure problem:** $\overline{\boldsymbol{\mathcal{E}}} = \alpha \overline{\mathbf{B}} - \eta_{turb} (\nabla \times \overline{\mathbf{B}})$

$$\underbrace{\alpha = -(\tau/3) \langle \mathbf{u} \cdot \omega \rangle;}_{\text{alpha-effect}} \quad \underbrace{\eta_{turb} = (\tau/3) \langle \mathbf{u}^2 \rangle}_{\text{Turbulent diffusion}}$$

- **Galactic Shear generates** B_ϕ **from** B_r
- **Supernovae drive HELICAL turbulence** (**Due to Rotation + Stratification**)
- **Helical motions generate** B_r **from** B_ϕ
- **Exponential growth of** $\overline{\mathbf{B}}$, $t_{growth} \sim 10^8 - 10^9$ yr

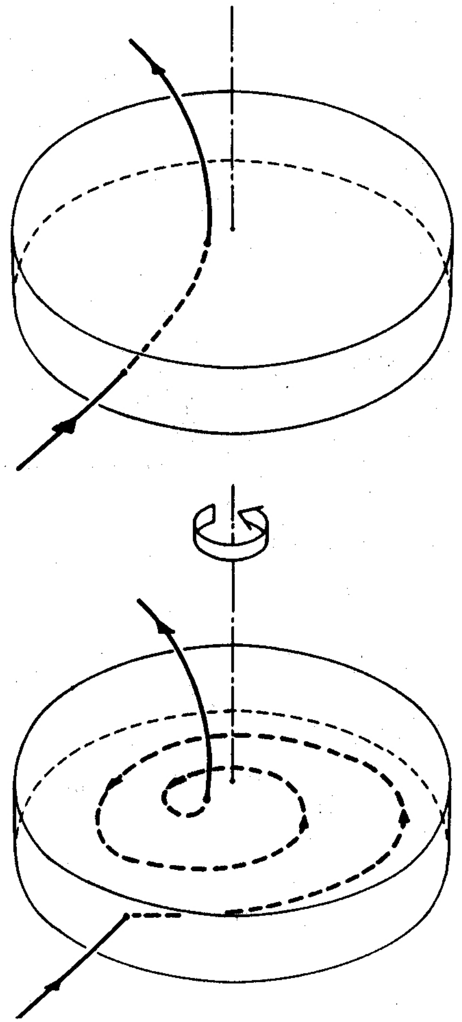
IUCAA

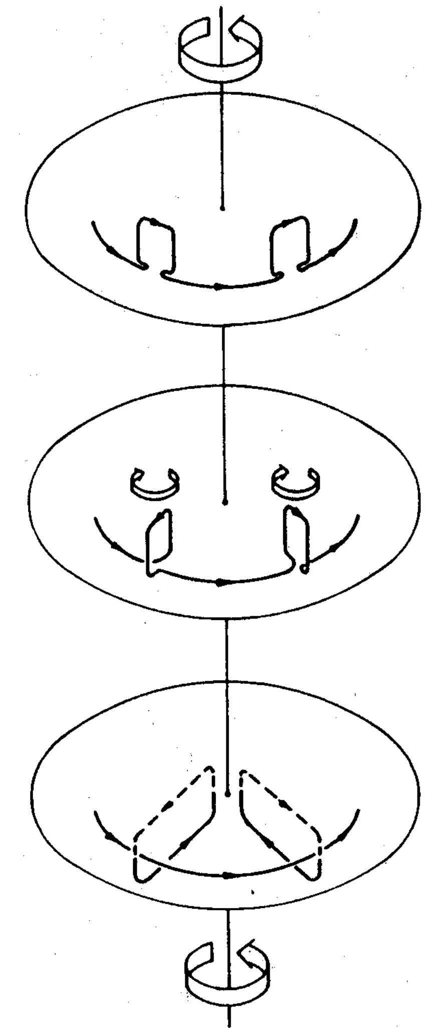
Supernovae Drive Helical turbulence



- **In galaxies supernovae drive turbulence**
- **Rotation + Stratification makes turbulence helical**

Large scale turbulent galactic dynamo





Kinematic Limit?

Helicity (links) conservation? Mean field in presence of noise?

Helicity and dynamo quenching

Anvar and Natasha Shukurov 2009

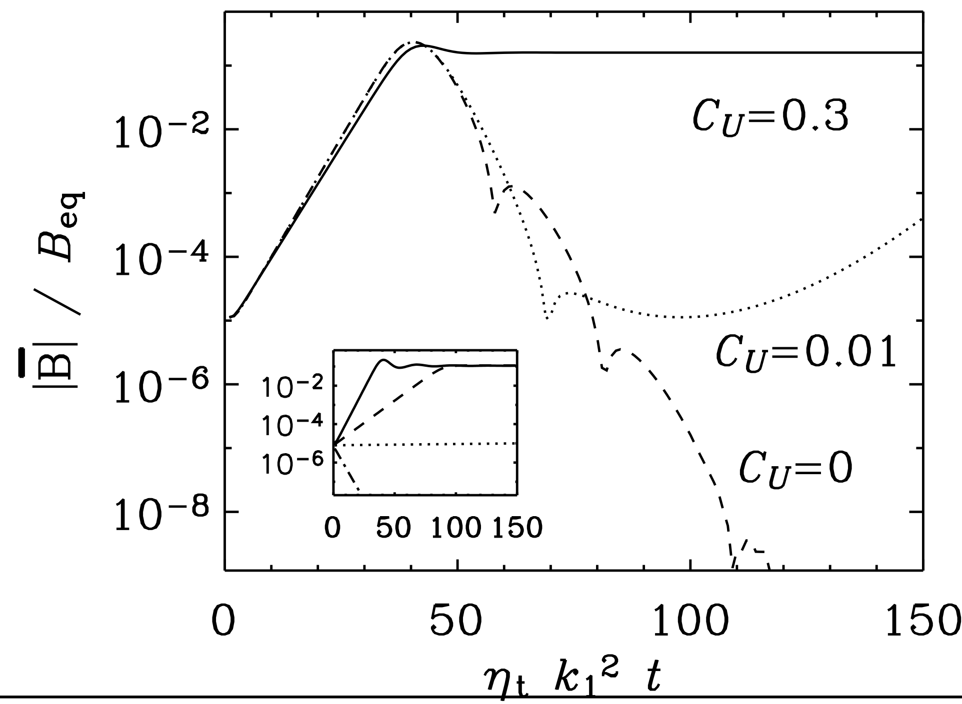
- Helical motions transfer helicity between WRITHE AND TWIST Helicities
- Lorentz force of small-scale twist Helicity grows to kill the dynamo
- Unless one has helicity fluxes

Helicity flux aleviates dynamo quenching

- **But what is gauge invariant helicity density and flux?**
- **Small scale helicity density h is density of correlated b field links** (Subramanian & Brandenburg, ApJ Lett., 2006)

$$\partial h/\partial t + \nabla \cdot \mathbf{F} = -2\overline{\mathcal{E}} \cdot \overline{\mathbf{B}} - 2\eta\overline{\mathbf{j} \cdot \mathbf{b}}$$

- **Fluxes due to simple advection could be important** (Shukurov, Sokoloff, Subramanian, Brandenburg, AA Lett., 2006)



IUCAA

IUCAA Linking number is
$\mathbf{(4 \times 1) + (4 \times -1) = 0}$!!

Summary

- The Universe is magnetized
- Early universe / Cosmic batteries make the first seed fields
- Supernovae/AGN driven Outflows? But need efficient dynamo action.
- Dynamos required to amplify/maintain fields.
- Can dynamos lead to coherent fields on saturation?
- Magnetic helcity needs to be shed to make large-scale dynamos work
- How to do mean field theory in presence of strong noise?
- How strong a role does the Early universe play?